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Design of Microwave Electromagnetic Sensor for Liquid Characterization

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Abstract

The design, fabrication, and testing of a highly sensitive GHz sensor for real-time measurement of engine oil quality are presented in this paper. The proposed microwave sensor is constructed on symmetric square slots structures, to improve the performance of the sensor. Using the resonant perturbation theory, the change in the max E field of test samples produces the frequency shift. The footprint of the designed sensor is (0.5523 λ_{eff} × 0.0920 λ_{eff}) where λ_{eff} is the effective wavelength value calculated at the operating frequency of 5.52 GHz. The oil sample adulteration analysis is done by immersing a dielectric probe up to a reference level of 20 mm. Thus, the dielectric behavior of the sensor is estimated with an average sensitivity of 1.7. The performance of the microwave sensor is evaluated by submerging it in different engine oil samples, thereby resulting in frequency shifts from 5.53 to 4.87 GHz. The results obtained from it indicated that the sensor has a quality factor of 58.55 and a FoM of 19.17. Thus, the proposed GHz sensor due to its good sensitivity, FoM, and quality factor is the eminent solution for the automobile industry.

Keywords: *Engine oil characterization; Relative Permittivity; GHz sensor; Sensitivity; Resonant perturbation theory*

1. Introduction

Engine oil is one of the vital components used in the automotive Industry. It helps to lubricate the moving parts by reducing friction between them, avoiding corrosion and engine cooling. When the engine oil gets adulterated by water, petrol, diesel, or rusted part of the engine then it leads to poor lubrication. Water is a primary pollutant in engine oil, which increases the permittivity values when measured. If engine oil quality is not monitored, it causes the seizing of the engine. By keeping a check on the engine oil quality, the lifetime and efficiency of the mobile are increased.

In the recent years, there exist a growing demand for liquid characterization using microwave sensors. Gigahertz (GHz) radiation produces an electromagnetic field that has an operating frequency range of 300MHz-30GHz. When the samples of engine oil are subjected to microwave

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radiation the amount of radiation reflected varies depending on the relative permittivity values of the sample. It has attracted the interest of many researchers due to its low cost, compact size, accuracy, fabrication, and testing ease. When operated on a narrow band, it provides high precision and utilizes a dense electric field for sensing. This research is focused on the development of such a GHz sensor for detecting engine oil quality. The sensor when loaded with different oil samples has a shift in resonant characteristics (reflection coefficient, bandwidth) due to GHz radiation incident on them. In this research, for evaluating the performance, the derived parameters such as quality factor, sensitivity, and figure of merit are utilized.

The researchers in (Kim et al., 2022), have proposed a volume-independent microwave sensor having a dimension of 218 × 214 mm is fabricated at the resonant frequency of 1.08 GHz. The polystyrene substrate of thickness 2.5 mm with relative permittivity $\varepsilon_r = 2.6$ with a rectangular slot on the top produces a sensitivity of 1.04 regardless of liquid under test volumes. A microfluidic sensor comprises SRR loaded splitter/combiner configuration resonating at 1 GHz with dimensions of 86 mm × 62 mm as shown in (Velez et al., 2017). This sensor utilizes the frequency splitting concept to demonstrate the viability and functionality of microfluidic sensors. The designed microwave sensor demonstrates the performance characteristics values of quality factor 28 and sensitivity of 0.195. Two practical real-time and high-precision multipurpose liquid sensors in (Kim et al., 2022), with a sensor dimension of 70 mm × 70 mm resonating at a frequency of 4.668 GHz are fabricated for a multitask chemical sensing of liquid mixtures. The designed sensor works on the principle of dielectric shift behavior resulting wider bandwidth of 288 MHz which produces higher sensitivity at lower costs. A metamaterial-based sensor for detecting NaCl and $C_2H_4O_2$ levels with dimensions of 55.64 mm × 63.70 mm operating at 2.43 GHz is proposed in (Zarifi et al., 2015) The ground plane is modified by metallic rings for the improvement of frequency bandwidth from 1.8 GHz to 4.2 GHz. This sensor contributes in controlling the impurities for a wider frequency range. In (Karatepe et al., 2020), a planar sensor proves to be an efficient solution by introducing the Sierpinski fractal curve structures operating at 4.13 GHz with dimensions of 100.3 mm × 28.3 mm. The Sierpinski fractal curve geometry is used on different substrate materials resulting in four distinct resonances with sensitivities of 11.3, 27.1, 70.3, and 53, respectively. Using the sensor sensitivity curve, the permittivity of unknown samples can be determined.

The researchers in (Abdulsattar et al., 2021) proposed a miniaturized resonator based on the Moore fractal geometry for water detection in crude oil. The footprint of the proposed sensor is 50mm × 50 mm using FR-4 substrate resonating at 0.8 GHz. In order to maximize the effective interaction area with the sample under test (SUT), the fractal geometry is designed to generate the maximum electric field fringing. With small liquid volume content, the proposed sensor becomes a very good option for detecting low concentrations of water, roughly 10% in crude oil. An aluminum sensor has a cavity body of length 47.5 mm and height of 40 mm where samples are inserted that resonate at 5.35 GHz in (Ivanov et al., 2019). The particle contamination in the lubricating oil is evaluated by considering the dielectric and resonant properties of the oil under test. This work has a better-quality factor of 1.43 × 10^4 and a sensitivity of 0.04 as compared to other works. Furthermore, coupled symmetric rectangular ring structure with dimensions of 52 mm × 23 mm resonating at 5.62 GHz is designed for the characterization of the dielectric permittivity of vegetable oils as reported in (Li et al., 2022). By exploiting the capacitive coupling between the two symmetric microstrip rectangular rings results in better sensitivity of 35 MHz and a quality factor of 232. A transmission line-based sensor in (Bhatti et al., 2022), with dimensions of 35 mm × 30 mm resonating at 5.25 GHz is employed for adulteration detection using the dielectric spectroscopy technique. Using the two-port networks, the adulteration of pure olive oil samples is detected using the maximum sensitivity of 4.6, bandwidth range of 530 MHz, and quality factor of 39. A substrate-integrated waveguide [SIW] with dimensions of 35 mm × 25 mm is proposed in (Loconsole et al., 2021) for the detection of water content in diesel fuel applications. This SIW sensor resonating at 9.76 GHz with a sensitivity of 1.39 is obtained from the characterization by means of appropriate radiating slots. A multiple complementary split ring resonator developed on FR-4 substrate with dimensions of 35 mm × 25 mm resonating at 2.45 GHz in (Javed et al., 2020). Owing to the capacitive effect, the value of dielectric material can be detected through resonant frequency shift. For accurate dielectric characterization of liquids, the sensor is designed to result in a sensitivity of 0.214 and a quality factor of 31.

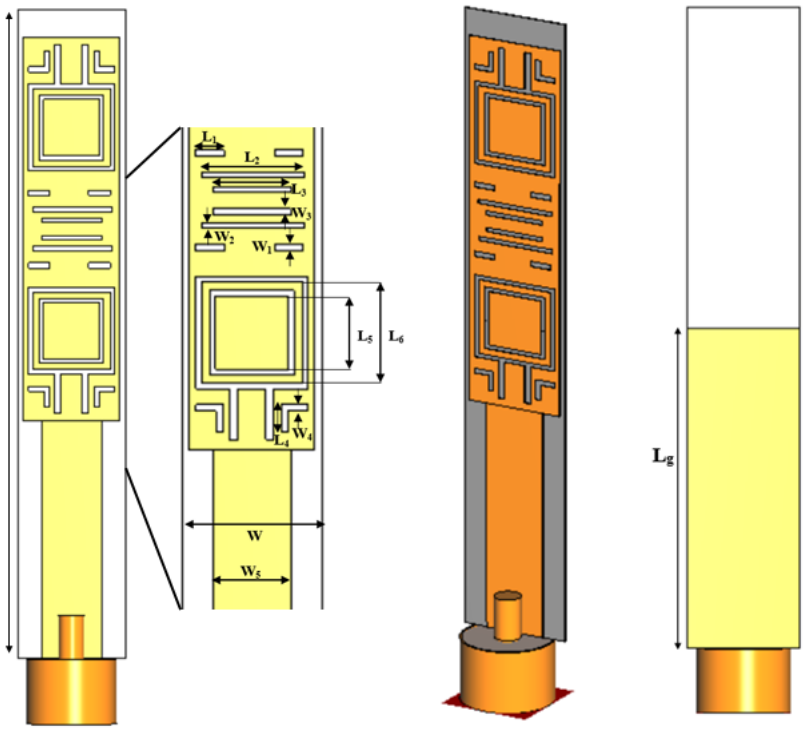

Figure 1. Proposed GHz sensor (a) Top view (b) Perspective view (c) Rear view

In (Zarifi et al., 2015), a ring based noncontact interface resonator is developed with a dimension of 27 mm × 27 mm operating at 5.50 GHz is used for liquid−liquid interface detection. Using the coupling technique, the resonator ring parameters like resonant frequency, quality factor, and signal amplitude are analyzed. Thus, the fabricated microwave noncontact interface sensor is used for the detection of oil sand applications with a sensitivity of 0.35 and a quality factor of 24. In (Raveendran et al., 2020), a metamaterial circular split ring resonator sensor resonating at 2.4 GHz whose dimensions are 30 mm × 20 mm. Using the resonant perturbation theory, the resonant frequency deviates by the electrical properties of the test samples. The varying dielectric behavior of the metamaterial sensor makes it suitable to detect close-range permittivity oil samples with a sensitivity of 74.875 MHz. A complementary split ring sensor is designed with the liquid samples to be placed normally on the sensor surface as reported in (Chuma et al., 2018). The footprint of the metamaterial sensor is of dimensions 20 mm × 28 mm resonating at 2.4 GHz. The difference in the voltage induced between the complementary split ring resonator (CSRR) and the ground plane impacts the resonant frequency shift for evaluating the adulteration of water content in ethanol. Owing to the increment of water content, the resonant frequency decreases from 2.35 to 2.3 although the quality factor increases from 35 to 47. The researchers in (Liu et al., 2020), proposed a microsensor of length 20.8 mm and width 13.4 mm. This work is based on the deriving relative permittivity values from impedance information obtained where a linearity value of 0.98 is achieved. A metamaterial sensor of dimension 10.16 mm × 22.86 mm is designed at (Qureshi et al., 2021) which resonates at 8 GHz. A tri-circle SRR structure is derived for better characterization of oil samples with a sensitivity of -83 dB(mg/L). In (Islam et al., 2021), a metamaterial-based split ring resonator with a microstrip transmission line sensor of dimension 8 mm × 12 mm is fabricated which operates at 30 GHz with a sensitivity of 1.12 GHz. In (Mejri and Aguili, 2018) a coaxial line of length 62.5 mm resonating at 2.25 GHz frequency. Its design is based on the deriving the relative permittivity data from the coaxial line's resonant frequency. By using this technique, the oil degradation is evaluated resulting in the frequency shift from 2.37 GHz to 1.49

GHz and r changing from 2.50 to 2.59. A microwave sensor with a dipole structure of length 59.73 mm which facilitates real-time monitoring and operates at a 2.4 GHz frequency range is reported in (Abdulsattar et al., 2021). The operating principle depends on the variation of relative permittivity value with respect to the dipole's varying resonance frequency. This frequency shift helps in evaluating the engine oil quality using the sensor for real-time monitoring. By using this sensor, the frequency shift is observed from 1.945 GHz to 1.89 GHz and ε_r from 1.667 to 1.765 indicating the refilling of engine oil.

In this paper, a highly sensitive, miniaturized microwave sensor is designed and analyzed. A figure of merit (FOM) is a performance metric that characterizes the performance of a device, system, or method, relative to its alternatives is also measured for our sensor. The proposed sensor focuses on impurities in oil, such as water, petrol, and diesel. The work is mainly based on the size miniaturization of the sensor. It clearly distinguishes between pure engine oil and adulterated engine oil. The permittivity values obtained from the VNA analyzer are displayed for engine oil samples. The rest of the manuscript is organized as follows: Section 2 presents the design and characterization of the proposed sensor. The experimental setup is analyzed in Section 3. Section 4 presents the results and discussion of the proposed work. The performance characteristics of the sensor are also discussed. The comparison regarding other similar works was also tabulated in the section.

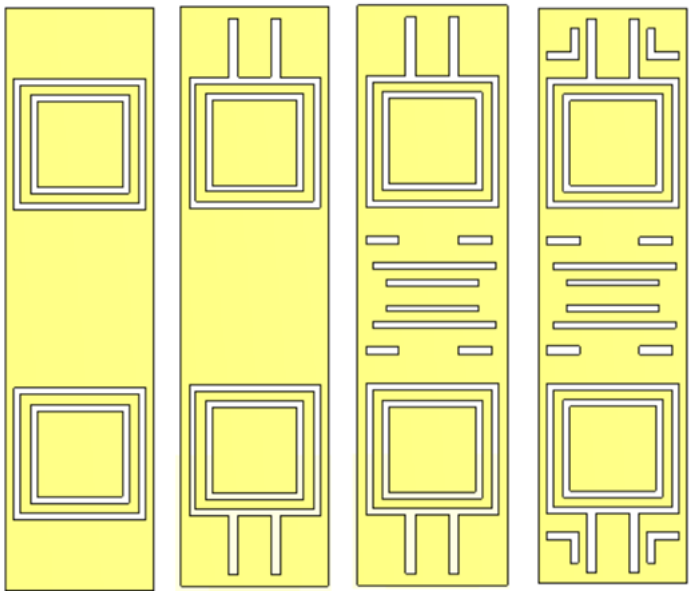

Figure 2. Evolution of the proposed GHz sensor (a) Resonator 1 (b) Resonator 2 (c) Resonator 3 (d) Proposed Resonator

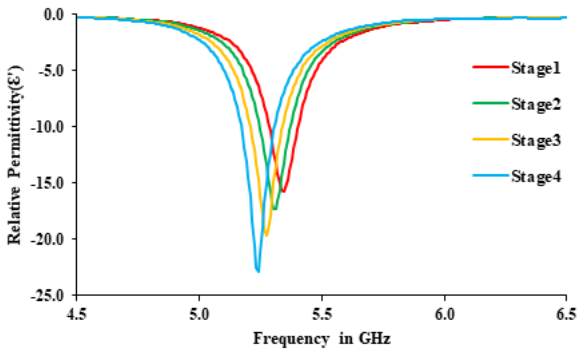

Figure 3. Reflection Coefficient S_{11} for various stages of evolution

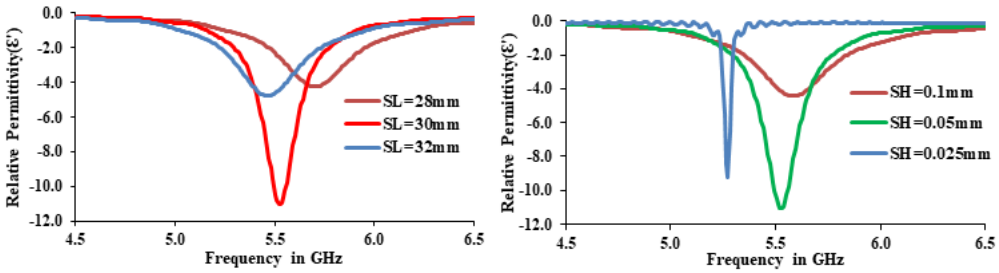

Figure 4. Parametric analysis

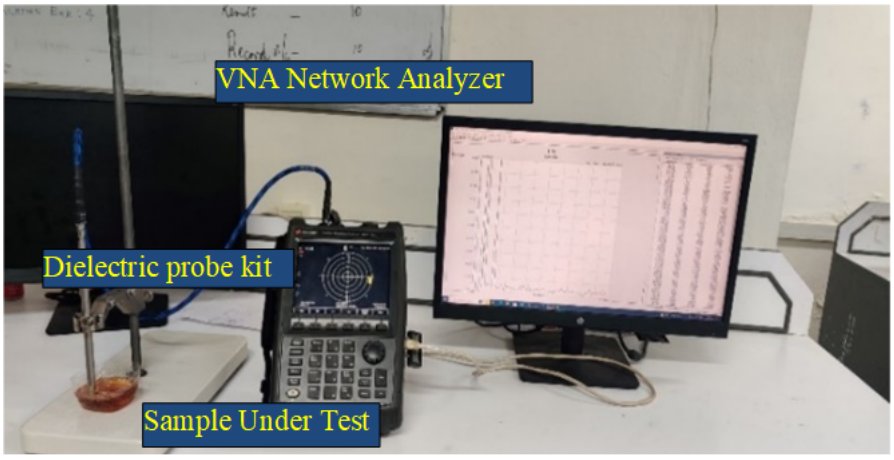

Figure 5. Experimental setup of VNA network analyzer for dielectric measurement

2. Sensor Design

2.1. Unit Cell Characterization

The proposed novel sensor design geometry is shown in Fig. 1. The sensor comprises concentric square slots along with two extended capacitor slots attached to the outer slot. Multiple capacitive slots of varying dimensions are positioned above the square slot. An L shape slot is also made on each corner with a length of 0.96 mm and a width of 0.24 mm. The resonator part has two symmetrical square structures which are mirrored with respect to the center point of the radiating structure. The sensor is developed on a polyimide substrate with a relative permittivity value of $\varepsilon_r = 3.5$, and a thickness of 0.05 mm. The partial ground plane is designed with a dimension of 15 mm × 5 mm. The optimized footprint of the proposed sensor is 30(L) mm × 5(W) mm. The copper thickness for the ground plane and microstrip line is fixed at 0.035 mm. Resonant perturbation theory states when a test specimen is kept in an area of the maximum electric field, the electrical characteristics affect the resonant frequency. Depending on this perturbation theory, the sensor is developed using 3-dimensional electromagnetic software-CST microwave studio. The overall geometric details of the sensor are mentioned in Table 1.

Table 1. Optimized Dimensions of the Proposed Sensor

Parameters	L_1	L_2	L_3	L_4	L_5	L_6	L_g
Value(mm)	1.00	3.70	2.80	0.96	2.60	3.00	5.0
Parameters	W_1	W_2	W_3	W_4	W_5	SL	W
Value(mm)	0.25	0.20	0.20	0.24	2.80	30.00	15.0

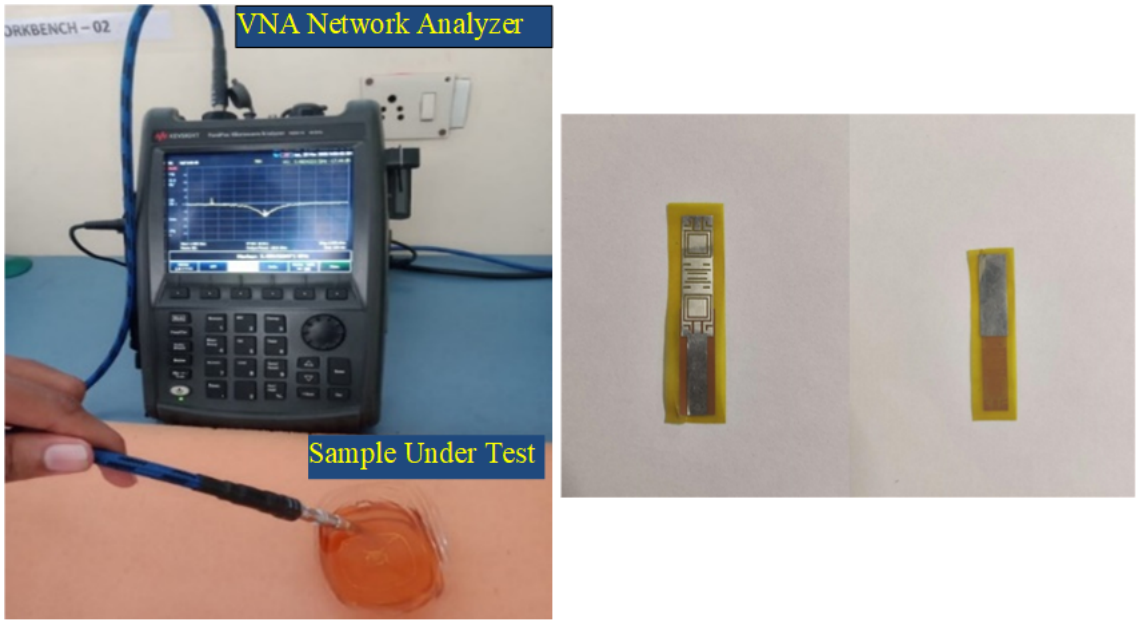

Figure 6. Experimental setup of fabricated prototype for dielectric measurement

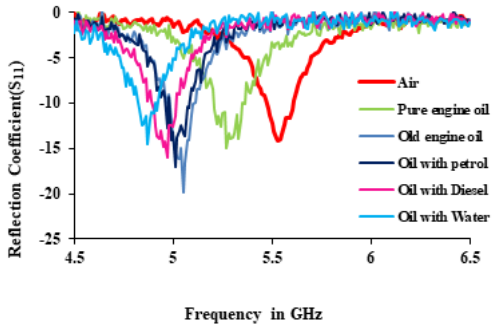

Figure 7. Reflection Coefficient S_{11} for various engine oil sample

2.2. Evolution

In this research, the sensitivity enhancement is achieved with a concentric square structure as depicted in (Ivanov et al., 2019). The evolution of the sensor is initiated by designing concentric square slots of side length $L_5 = 2.6$ mm and $L_6 = 3$ mm as shown in Fig. 2(a). The square slots were mirrored with respect to the center point with produces an S_{11} value of -9.76 dB. As a next step in development, two vertical slots were attached to the outer slots on either side which is shown in Fig. 2(b) which slightly improves the S_{11} value to -9.809 dB. The next step consists of introducing several slots in the middle part of the resonator of varying lengths $L_1 = 1$ mm, $L_2 = 3.7$, $L_3 = 2.8$ mm, and width of $W_1 = 0.25$, W_2 and W_3 is 0.2 mm. This structure of the sensor is shown in Fig. 2(c), which further increases the return loss value to -10 dB. As a final stage in the evolution process L-shaped slots of length 0.96 mm and width, 0.24 mm were deployed at each corner of the resonator. The final resonator structure is shown in Fig. 2(d), with a return loss value of -11.06 dB.

2.3. Parametric Analysis

The microstrip sensor is analyzed to achieve a return loss of less than -10 dB by performing parametric analysis. By varying the SL value between the range of 28 to 32 mm the parameter is optimized to resonate at 5.53 GHz. For the SL value of 28 and 32 mm, the S_{11} parameter is

above -10 dB which is not suitable for sensing operation. Hence, SL equal to 30 mm is fixed as the optimized value. Similarly, the substrate thickness is fixed as h = 0.05 mm after performing parametric analysis. The thickness values SH = 0.025 mm and 0.1 indicates the resonant frequency shifts from the desired as well as resonating above -10 dB. Hence, using the substrate thickness as h = 0.05 mm, the S_{11} parameter is resonating below -10 dB at 5.53 GHz as shown in Fig. 3.

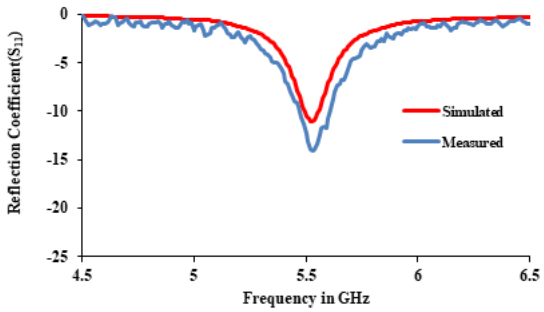

Figure 8. Simulated Vs Measured Reflection Coefficient S_{11} in Free Space

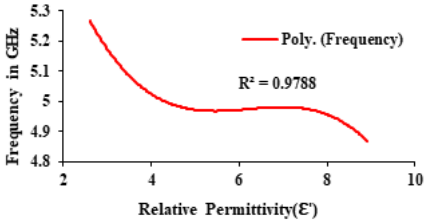

Figure 9. Permittivity for various frequencies and polynomial curve fit

Table 2. Tabulation of Frequency Shifts for Various Samples

Medium	Return loss(dB)	Resonant Frequency (GHz)	Frequency Shift (GHz)
Air	-14.10	5.53	–
Oil	-14.27	5.27	0.26
Old Oil	-19.22	5.05	0.48
Oil with Petrol	-17.09	5.009	0.521
Oil with Diesel	-14.61	4.97	0.52

3. Experimental Setup

Polyimide is chosen as the substrate owing to its characteristics like thermal stability, chemical resistance, and high wear resistance having a relative permittivity of 3.5 and thickness of 0.05 mm. The variations in the dielectric properties of the oil samples under detection are used as a sensing parameter. Measurement of dielectric constant values of the oil samples is useful for the analysis of the sensing mechanism of the proposed sensor. Another technique used to detect adulteration of oil is done by using a microwave sensor with frequency shift as a sensing parameter. For measurement of dielectric values, a Keysight network analyzer (model: N9951A) and a dielectric probe device (model: Agilent 85070 E) are used as shown in Fig. 4. Initially the analyzer was calibrated using open, short conditions for normalization under the frequency of 4.5 – 6 GHz. In the next step, distilled water was used as an immersive medium for the correct calibration of the device. Figure 5 represents the experimental setup of the fabricated prototype for the measurement of the dielectric properties of different oil samples. The sensor's single port feature makes it feasible for

Table 3. Comparison Table for Reflection Coefficient

Medium	Simulated		Measured	
	Return loss(dB)	Resonant Frequency (GHz)	Return loss(dB)	Resonant Frequency (GHz)
Air	-11.06	5.528	-14.10	5.53

Table 4. Measured Performance Characteristics

Medium	Bandwidth (GHz)	Q	Sensitivity (%)	HPBW (GHz)	FoM
Air	0.12	46.08	-	0.24	-
Pure oil	0.09	58.55	1.7	0.18	19.17
Petrol Oil	0.02	250.45	0.3	0.16	1.875
Water Oil	0.07	69.57	1.2	0.17	7.058
Old Oil	0.06	84.16	1.1	0.13	8.461
Diesel Oil	0.06	82.83	1.2	0.18	6.667

direct immersion in the oil samples while also discriminating the samples with close permittivity values.The results obtained using various samples are listed in Table 2.

Table 5. Performance Comparisons With Other Relevant Works

References	Size (mm×mm)	Resonant Frequency (GHz)	Quality factor	Sensitivity
(Chuma et al., 2018)	86 × 62	1	28	0.195
(Zarifi et al., 2015)	55.64 × 63.70	2.53	20	0.05
(Bhatti et al., 2022)	35 × 25	2.4	45	0.214
(Raveendran et al., 2020)	27 × 27	5.5	24	0.35
(Velez et al., 2017)	20 × 28	2.3	48	0.036
Proposed Work	**30 × 5**	**5.53**	**58.55**	**1.7**

4. Results and Discussion

4.1. Frequency Analysis of oil samples

Oil samples with different impurity levels were considered for the study of the dielectric properties of the proposed sensor. Adulterated oil content such as petrol, diesel, and water are used as test samples. The fabricated sensor is submerged in 40 mL of various oil samples up to a reference level of 20 mm and frequency shift is recorded for each sample as shown in Fig. 6. In order to validate the adulterated content of oil samples, the sensitivity parameter of the fabricated microwave sensor is utilized. Initially, the reflection coefficient of the fabricated prototype is measured under open air condition is obtained as 5.53 GHz. The comparison of the simulated and experimental results of the reflection coefficients of the fabricated sensor is found to be in good agreement as shown in Fig. 7 and also tabulated in Table 3.

4.2. Analysis of sensor performance parameters

For the detection of oil adulteration, 3 important parameters namely sensitivity, Q-factor, and FoM are considered for analysis.

$$Q = \frac{f_c}{f_b} \tag{1}$$

where f_c is the resonant frequency and f_b is frequency bandwidth. The Q factor or quality factor of a tuned circuit (which includes antennas) measures how many times the current passes through the circuit.

$$f_b = f_h - f_l \tag{2}$$

where f_h is the higher cutoff frequency and f_l is the lower cutoff frequency.

$$S = \frac{f_{empty} - f_{sample}}{f_{empty}(\varepsilon_r - 1)} \tag{3}$$

where f_{empty} is the resonant frequency in the air medium, f_{sample} is the resonant frequency in the sample under test and ε_r is the dielectric constant value of the sample under test. The level to which resonant frequency shifts whenever the medium changes i.e., permittivity of the medium changes.

$$FoM = \frac{Sensitivity}{HPBW} \tag{4}$$

where HPBW is the half power beam width in the sample under test. A figure of merit (FoM) is a performance metric that characterizes the performance of a device, system, or method, relative to its alternatives. The transmission line-based structures work on the principle of change in the E and H field. The characterization of oil samples is significantly influenced by the electric field characteristics. The microwave sensor is designed as a single network submerged directly in the oil samples so that the E-field is in direct contact with the resonator. When the EM wave is fed, the patch structure contributes to the conductive region while the slot structures act as the capacitors. This inductive and capacitance effect decide the resonant frequency which makes the sensor act as a narrow-band stop filter. The overall capacitance of the sensor is altered by submerging the resonator part in oil samples that results in frequency shifts as depicted in Fig. 7. Using this immersion method, the sensitivity is found to be 1.7 which is better when compared with (Velez et al., 2017), (Zarifi et al., 2015), (Karatepe et al., 2020), (Abdulsattar et al., 2021), (Ivanov et al., 2019), (Li et al., 2022), (Bhatti et al., 2022), (Loconsole et al., 2021), (Javed et al., 2020), (Raveendran et al., 2020) & (Chuma et al., 2018). When the impurities in the oil sample vary, the resonant value shift to lower frequencies. Thus, the bandwidth, Q-factor, and FoM obtained from the proposed sensor are found to be 0.09 GHz, 58.55, and 19.17, respectively. With the increase in the adulteration, the Q-factor increases whereas the sensitivity values. The Q-factor observed is in good agreement in comparison with (Velez et al., 2017), (Bhatti et al., 2022), (Zarifi et al., 2015), (Raveendran et al., 2020) & (Chuma et al., 2018). The calculated values of the Q-factor, sensitivity, and FoM were tabulated in Table 4.

4.3. Curve Fit Analysis

The curve-fitting graph as shown in Fig. 8, depicts the relationship between relative permittivity and frequency. By using polynomial curve fit as the optimal one, the R^2 value is evaluated as 0.9788. Thus, the relationship between permittivity and frequency is given by the Equ. 5

$$0.0072\varepsilon^3 - 0.1336\varepsilon^2 - 6.6169 + f = 0 \tag{5}$$

Table 5 shows the comparative performance analysis work of the proposed sensor with other previously reported works. It is evident that our sensor provides better sensitivity, and improved quality factor, on a low-cost substrate, making it an appropriate element for oil detection.

5. Conclusion

This research proposed a low-cost, easy-to-fabricate symmetric square slot microwave sensor with Polyimide substrate resonating at a frequency of 5.53 GHz for adulteration detection of engine oil. The sensor is working based on the principle of resonant perturbation theory. The dielectric behavior is analyzed, by immersing the dielectric probe resulting in the permittivity shift from 2.2 to 2.5. Using single port topology, the sensor is immersed in various oil samples. The pollutants were intentionally added to pure engine oil to measure the shift in frequency from 5.53 GHz to 4.87 GHz. The simulated and experimental results of the sensor under oil characteristics and impurity detection are in good agreement. With that, sensing parameters such as sensitivity, Q-factor, and FoM were calculated for different samples of oil. Thus, the sensitivity values of 1.7, Q-factor value of 58.55, and figure of merit (FoM) value of 19.17 is obtained. These results show that the proposed sensor can be used for engine oil characterization and purity detection for the safe operation of automobiles.

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